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Predicted Extreme High Tides for Mixed-Tide Regimes

B. D. ZETLER

Scripps Institution of Oceanography, La Jolla, CA 92093

R. E. FLICK

California Department of Boating and Waterways, Scripps Institution of Oceanography, La Jolla, CA 92093

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ABSTRACT

There are a number of published studies of the astronomical conditions prevailing when extreme high tides are predicted, but usually these are directed toward tidal regimes that are dominantly semidiurnal. The published criteria are found to be inadequate for mixed regimes (diurnal tides roughly the same order of magnitude as the semidiurnal tides in the area).

For the mixed tides on the California coast, added consideration must be given to tropic tides (diurnal tides larger than average when the moon is near maximum declination) and to the 18.61-year period of the lunar-node cycle. Furthermore, extreme high diurnal tides tend to occur when the sun is near maximum declination (summer and winter) whereas comparable semidiurnal tides ordinarily occur near the equinoxes (spring and fall). Because of these added complications, harmonic tide predictions were prepared for four California ports up to the year 2000 so that information on extreme high tides could be tabulated. These data help to alleviate public fears that tidal contributions to the disastrous flooding in California in 1982–83 would be exceeded in the following decade.

1. Introduction

During the winter of 1982–83, a combination of high tides, higher-than-normal sea level and storm-induced waves were devastating to the coast of California. Newspaper accounts of the damage referred to predictions of even higher astronomical tides in the early part of the next decade and led to increased public concern as to the safety of many coastal structures. There were numerous requests to Scripps Institution of Oceanography for definitive forecasts of extreme astronomical tides.

An investigation as to the source of the published alarming forecasts disclosed they were derived from a book, *The Strategic Role of Perigean Spring Tides,* by Wood (1978). Wood's study had searched for dates on which spring tides (due to conjunction of the sun and moon) would coincide with extreme perigee (moon unusually close to the earth and termed "proxigree" by Wood). Both of these phenomena do indeed contribute to forecasts of extreme high tides, but other criteria must be considered for areas having large diurnal components in the tide, such as the California coast. Most of the published studies on astronomical extreme high tides, as for example that by Amin (1979), also concentrate on semi-daily criteria. However, Cartwright (1974) considered the greatest tide-raising forces as well as peak semi-daily tides. His criteria for greatest tide-raising forces were so stringent that he selected only eight dates for the the period, 1 to 4000 AD, and finally reduced this number to two, 1340 and 3182.

Since our immediate problem was to resolve whether tides on the California coast in the immediate future (up to the year 2000) would greatly exceed those during the winter of 1982–83, it was decided that harmonic tide predictions would be prepared for four California ports, San Diego, Los Angeles, San Francisco and Humboldt Bay, up to and including the year 2000. Monthly and annual extreme highs could then be tabulated. A summary of the results is in press (Zetler and Flick, 1985). This paper, condensed to a technical note, omits much of the pertinent scientific aspects of the results and the present paper has been prepared to make these available.

2. Discussion

The California coast has a mixed tidal regime, which means that the amplitude of the diurnal constituents is of the same order of magnitude as the semidiurnal constituents. By one standard measure (Defant, 1961) the tides are mixed when the ratio $F = (K_1 + O_1)/(M_2 + S_2)$ lies between 0.25 and 3.0. On the California coast, $F \approx 0.7$. The constituents are defined in the Appendix; see also Hicks (1984).

Just as spring and perigean tides refer to large semi-daily ranges, tropic tides are large semi-monthly diurnal tides that occur when the moon is near

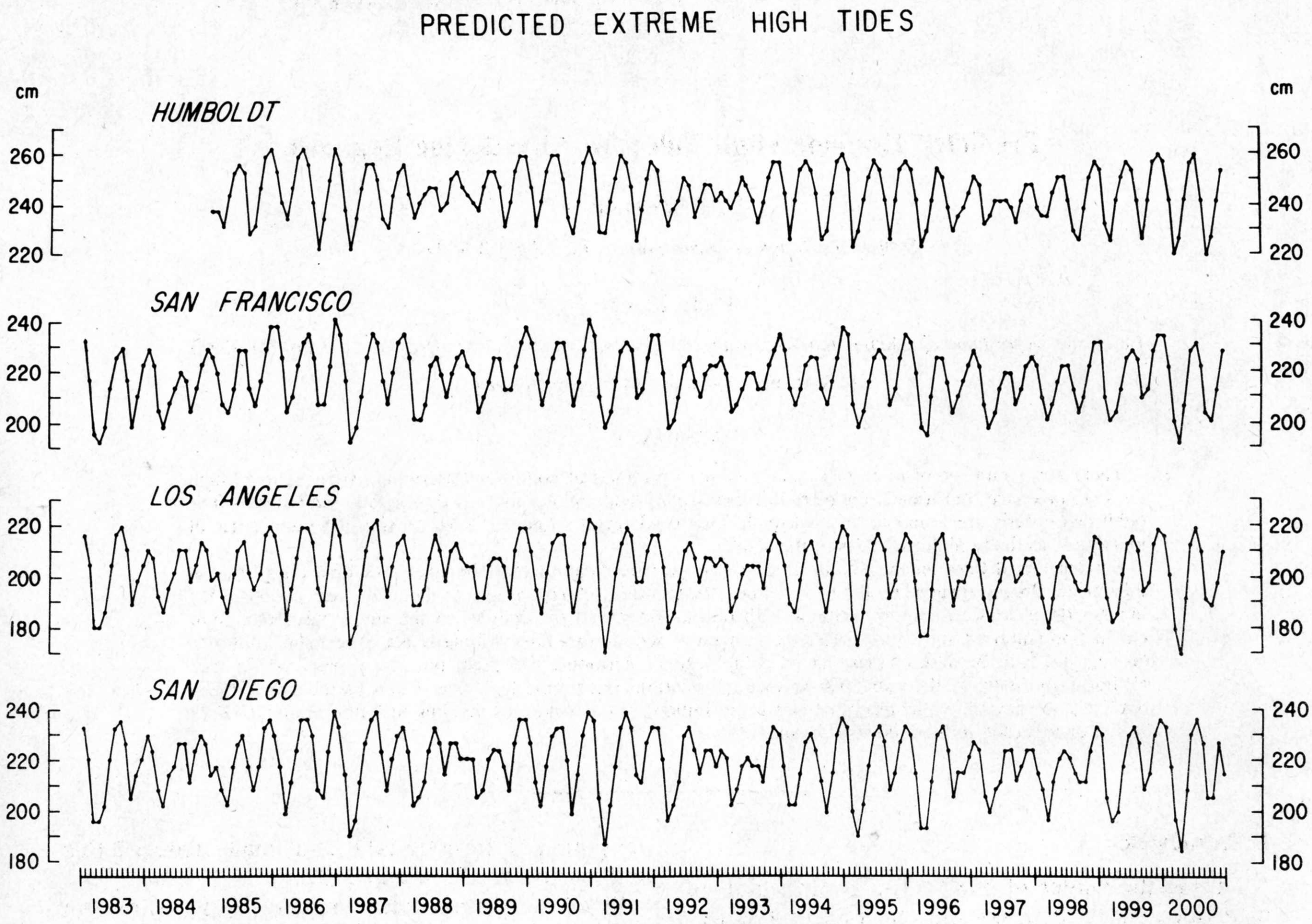

FIG. 1. Predicted monthly extreme high tides for four California ports. The semiannual, 4.4-year and 18.61-year variations are a consequence of the mixed tidal regime on this coast.

extreme declination, both north and south. In terms of the harmonic constituents, spring tides occur when S_2 and M_2 are in phase, while tropic tides correspond to K_1 and O_1 in phase. Tropic tides occurring in December and January tend to be particularly large because this is the time of perihelion (earth's closest yearly approach to the sun). The constituents K_1 and P_1 are in phase at this time, and again in June and July thus increasing the tropic tide range both in winter and summer. In contrast, the spring-tide ranges are enhanced during the time of the equinoxes, in March and September when the constituents K_2 and S_2 are in phase.

Figure 1 is a plot of the monthly extreme highs at the four California ports. It shows clearly that the annual extremes usually occur in winter and occasionally in summer, but never in the spring and fall when maximum spring tides occur. This emphasizes the importance of considering the diurnal tidal species on the California coast.

Inspection of Fig. 1 shows that all four stations display a marked semiannual beat in extreme tide, peaking in summer and winter. The details of each graph vary, since the exact shape depends on the local amplitude and phase of each constituent. Indeed, the Los Angeles and San Diego traces show years with secondary peaks in the spring and fall (1992–93, for example) as a result of enhanced spring tides. This completely obscures the semiannual variation in sea level due to S_{sa} (range 3 to 6 cm) and masks the annual variability due to S_a (range 12 to 15 cm). There is an obvious cyclical variability of about 4.4 years which Cartwright (1974) ascribes to "passages of the longitude of (lunar) perigee past the equinoxes," either vernal or autumnal. Note that this cycle peaked in 1982–83, contributing to the coastal flooding in California. Finally, the 18.61-year lunar-node cycle is apparent with the highest annual maxima in the 1986–90 period and the lowest annual maxima 9 years later.

The 18.61-year node cycle has another interesting aspect in distinguishing between the relative contributions of diurnal and semidiurnal species to extreme high tides. Table 1 shows amplitude increments due

TABLE 1. Tidal height contribution from lunar node (f-factor) anomaly for San Diego, 1987.

Principal lunar constituent	Amplitude (cm)	×	f-factor anomaly*	=	Tide heights [augmentation (+) or diminution (−)] (cm)
Diurnal tides					
K_1	35.20		+0.112		+3.94
O_1	22.25		+0.182		+4.05
Q_1	4.08		+0.182		+0.74
Semidiurnal tides					
M_2	57.61		−0.036		−2.07
N_2	13.56		−0.036		−0.49
K_2	6.52		+0.315		+2.05
				Total	+8.22

* From Schureman (1958), Table 14.

to node factors for the largest lunar constituents in 1987, a year when the diurnal f-factors are greatest and the M_2 f-factor is the smallest (Schureman, 1958, Table 14). The net augmentation is 8.73 cm for the diurnals; for the semidiurnals, the net is only −0.51 cm because the K_2 anomaly offsets that of M_2. Thus the effect of the 18.61-year cycle is very small on semidiurnal tides but is a dominant factor for mixed tides. In the San Diego predictions, the maximum (238 cm) occurred in 1987 and adjacent years and the minimum (226 cm) in 1997, the year for which the diurnal f-factors are minimum and the M_2 f-factor is maximum. The net anomaly of these semidiurnal constituents is over an order of magnitude smaller than that of the diurnal constituents, and this explains why studies of extreme high tides in areas of dominantly semidiurnal tides have given little (if any) attention to the phenomenon of nodal modulation of the amplitudes of lunar constituents.

3. Conclusion

Because the criteria for estimating extreme high astronomical tides are so different and more complex for mixed tides than for semi-daily tides, it is best to prepare tide predictions and to extract the information required from the predictions if the time period for which estimates are needed is reasonably small. However, we have learned that for mixed tidal regimes, annual extreme high tides will usually occur in winter and sometimes in summer and, over an 18.61-year nodal cycle, the highest heights will occur in or near the years for which the diurnal f-factors are maximum.

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APPENDIX

Astronomical Tide Constituents

By convention, a subscript 1 indicates a constituent with a period about 24 hours (diurnal) and a subscript 2 indicates a constituent with a period about 12 hours (semidiurnal).

K_1—Lunisolar diurnal constituent

O_1—Lunar diurnal constituent

P_1—Solar diurnal constituent.

The constituents K_1 and O_1 express the effect of the moon's declination. Together they account for diurnal inequality, and in the extreme, for diurnal tides. They differ in frequency by 2 cycles per month. The constituents K_1 and P_1 express the effect of the sun's declination. They differ in frequency by 2 cycles per year.

M_2—Principal lunar semidiurnal constituent that represents the rotation of the earth with respect to the moon.

S_2—Principal solar semidiurnal constituent that represents the rotation of the earth with respect to the sun. The frequencies of M_2 and S_2 differ by 2 cycles per month and their beat represents the spring-neap tide cycle.

K_2—Lunisolar semidiurnal constituent that modulates the amplitude of M_2 and S_2 for the declinational effect of the moon and the sun, respectively. It differs in frequency from S_2 by 2 cycles per year.

S_a, S_{sa}—Solar annual and semiannual constituents that are mainly used to account for the seasonal, average meteorological influences of temperature and atmospheric pressure, etc. on sea level. As such they are referred to as "radiational tides" (Zetler, 1971).

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